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Development of methods of Producing Large Areas of Silicon Sheet by the slicing of Silicon Ingots using Inside-Diameter (I.D.)Saws.

FINAL REPORT

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ABSTRACT

I.D. wafering equipment, blades and processes were used to develop methods for producing large areas of silicon sheet.

Modifications to a 16 inch STC automated saw included:

- Programmable Feed System
- Crystal Rotating System
- STC Dyna-Track Blade Monitoring and Control System.

By controlling the plating operation and by grinding of the cutting edge, we were able to produce 16 inch I.D. blades with a cutting edge thickness of .22 mm. Crystal rotation mechanism was used to slice 100 mm diameter crystals with a 16 inch blade down to a thickness of .20 mm.

Cutting rates with crystal rotation were generally slower than with standard plunge I.D. slicing techniques. Using programmed feeds and programmed rotation, maximum cutting rates were from 0.3 to 1.0 inches per minute.

1.0 INTRODUCTION

The goal of this program was to develop methods of producing large areas of silicon sheet by slicing ingots using inside diameter (I.D.) saws. Most of the silicon sliced today is done so using the I.D. saw. Most of the wafers produced are for the semiconductor industry with some silicon being used for photovoltaics.

The semiconductor industry is highly competitive with many suppliers of silicon. Wafers cut for the semiconductor industry are usually 0.050mm to 0.075mm thick with flatness requirement of 10 to 20 microns. Thickness variations must also be controlled to about 10 microns. Although the cost of raw material is important to the semiconductor industry, the cost of material in the final device is only a small fraction of the total cost. Therefore, the quality of the wafer and its dimensional accuracy are as important as kerf loss and wafer thickness. In addition, semiconductor wafers must be of sufficient thickness to minimize breakage further down the processing line where many expensive manufacturing steps have been added to the silicon wafer.

With the present cost of raw materials, the cost of silicon is a significant portion of the cost of a photovoltaic cell, therefore, total consumption of silicon becomes a very

important factor in reducing the cost of producing silicon photovoltaic cells. The slicing process is also expensive due to the cost of the equipment, labor, utilities, consumable materials and factory overhead, therefore, the cost of material consumption must be compared to the add-on cost of slicing in arriving at an optimum process.

One of the methods used to reduce cost in this contract was to rotate the silicon ingot while it was being cut. The benefit of slicing while rotating the boule, is that the blade only penetrates one half the diameter of the crystal. This allows the use of a smaller diameter blade, (16 inch versus 22 inch) which have a thinner core (0.004 inches versus 0.006 inches respectively), and allows the use of a thinner cutting edge because blade deviation is not as critical.

The cutting edge of a blade (See Fig. 1) must normally be about 0.18mm wider than the core of the blade to allow removal of coolant and debris and to prevent the crystal or the wafer from rubbing on the core of the blade. Core rubbing deforms and weakens the blade. It is the primary cause of blade failure.

During rotational slicing, the blade can wander more without rubbing the core since it only penetrates one half the diameter. Another method we used to control core rubbing

was to monitor axial deviations in the blade during slicing using a non-contact gauge. Excessive blade wander was limited by dressing the blade when it exceeded present limits.

The feed rate and rotation rate were also varied during slicing to shorten the length of time it takes to slice an ingot. If the cutting rate is fixed, it is limited to the weakest point in the cut which is usually during entry and exit from the crystal. Once the blade has entered the crystal, the rates can be increased, to allow shorter cutting times. We also allowed programming of the crystal rotation rate to see whether rotation could be optimized.

Program goals were:

Ingot diameter	10cm
Wafer thickness	.24mm
Kerf loss	.24mm
Slicing speed	2.5cm per minute
Wafers per hour	20
Yield	90%

2.0 TECHNICAL DISCUSSION

2.1 Slicing Equipment

2.10 The I.D. Saw

A 16 inch automated I.D. slicing machine (Model SMA-4401) was installed to perform the work for this contract.

The automated feature of the saw was used to automatically recover the silicon wafers after they were sliced and load them into a cassette.

Since the rotated wafers were thin and did not have a graphite support beam as during plunge slicing, they had a tendency to adhere to the surface of the blade and break. The automated recovery system used a vacuum chuck to pull the wafer away from the blade after it had been cut.

The saw was also equipped with a programmable Electric Feed System, a Crystal Rotating Fixture and an STC Dyna-Track Blade Monitoring System.

2.11 Crystal Rotating System

The Crystal Rotating System has a precision spindle and gear motor integral with the mounting block. It fits into the ingot box in normal spring loaded manner. Gear motor provides full torque at all speeds, with speed regulation better than 1% of set speed over full load variation.

The crystal can be rotated from .15 to 150 RPM in CW and CCW directions.

The capacity is up to 5 inch diameter, with crystal length up to 16 inches.

Rotation rate can be programmed with a preshaped cam or can be set manually.

2.12 Electric Feed Actuator System

This system is an electro-mechanical closed loop servo system. Actuation is provided by a 1/8 H.P., D.C. gear motor driving a precision lead screw and nut assembly. The feed rate may be set manually or varied by the preprogrammed shape of a cam.

Cutting speed is infinitely variable from 0.5 to 35 mm per minute. Speed regulation is 1% of set speed or better. The preprogrammed cam can be shaped to suit. There is an overload slip coupling protection. The sealed drive train is drip lubricated.

The unit can be retrofitted to a standard machine. Controls include constant feed rate adjustment and minimum and maximum programmed rate. The unit can be run in the manual or programmed mode, by means of a toggle switch.

There are provisions on the feed system to accept two cams which travel the length of the cutting stroke. The cams are used to drive a pair of linear transducers. The feed rate and rotation rate are proportional to the displacement of the linear transducer in the programmed mode.

Maximum and minimum feed rates during programmed feed are controlled by a set of potentiometers on the control panel of the I.D. saw. The height of the cam can remain

the same for a variety of programmed feeds. The shape of the cam determines the position and the rate at which the feed rate is being changed.

2.13 Blade Monitoring System

The Blade Monitoring System continuously measures and records lateral runout of the cutting edge of the I.D. diamond blade to the nearest 0.0001 inch while slicing. Axial, or lateral, deflection of the cutting edge of an I.D. diamond blade is a major cause of work damaged silicon wafers. The problem can usually be easily corrected by dressing one or both sides of the blade. The monitoring system signals when the blade should be dressed and on which side. The system will also indicate when a blade requires tensioning.

The system consists of a highly accurate, non-contact deflection gauge, a strip chart recorder and an analog meter with plus/minus limit settings. Mounted on the STC machine head, the non-contact gauge continuously senses the axial deflection of the blade I.D. during slicing. The information is recorded on the strip chart, and displayed on the analog meter to the nearest 0.0001 inch (2.5 microns). The strip chart travels at a rate of 4 inches per hour. The plus/minus settings can be used to halt machine operation if they are exceeded.

2.2 Blades

All the blades manufactured for this contract were made with standard 0.10 mm stainless steel core material for a standard 16 inch hydraulic blade mount. Ordinarily, a 16 inch blade will have a cutting edge thickness from 0.25 mm to 0.30 mm. To reduce kerf losses below 0.24 mm, we manufactured blades with cutting edge thickness from 0.20 mm to 0.24 mm.

The optimum diamond particle size for blades are 325-400 U.S. mesh diamonds. Blades manufactured with smaller diamonds (400-500 U.S. mesh) do not cut as freely. The smaller size diamonds do not remove as much material and they do not have enough space between them to allow removal of coolant and debris. Larger diamonds cut quicker, however, they have a tendency to damage and break the wafers being cut. It is also impossible to make thin blades with larger size particles.

Typically, 325-400 U.S. mesh diamond particles range from 60 to 80 microns in size. If one layer of diamonds is plated on each side of a 0.10 mm core, the thinnest blades would range from 0.22 to 0.26 mm. In practice we were able to manufacture blades as thin as 0.20 mm. The diamonds tend to be cylindrical rather than blocky in shape and they tend to plate along their length.

Diamond particles plate symmetrically around the I.D. of the blade core so that the thickness of the cutting edge limits the amount of diamonds that are radially built up from the cutting edge. In order to provide enough diamonds to give good blade life, we plated a second layer of diamonds only on the cutting edge.

Our commercial blades have diamond build up of about 0.25 mm from the cutting edge. The thin blades that we manufactured had 0.10 to 0.15 mm of diamond buildup. We could increase to 0.25 mm by a second plating operation at the expense of increasing the cutting edge thickness.

The thickness of the cutting edge could also be reduced by grinding the blades in a special fixture. We found that blades that were moderately ground before use would work better and would be slightly thinner. The grinding operation removes some of the excess nickel on the sides of the blade and exposes diamond particles.

We achieved poor results when we tried to significantly reduce blade thickness by grinding the cutting edge. The blades were first plated to a thickness of 0.30 mm and subsequently ground to a thickness of 0.23 mm. We are not certain as to why the ground blades did not perform well. We think that the grinding is weakening the cutting edge and is fracturing the diamonds. The grinding

operation is also very expensive since a considerable amount of the grinding wheel is used up in grinding a few mils of diamond off the sides of the blade.

We manufactured a total of 25 blades for this contract. Below is a summary of the blade parameters.

BLADE SUMMARY

16 Inch I.D. Blades

Qty.	Core	Cutting Edge	Buildup	Type
2	0.004"	0.0080"	0.004	Single Plated
2	0.004"	0.0085"	0.007	Single Plated
2	0.004"	0.009"	0.007	Single Plated
4	0.004"	0.009"	0.009	D.P. Ground
3	0.004"	0.0095"	0.009	D.P. Ground
3	0.004"	0.0095"	0.006	Single Plated
5	0.004"	0.0095"	0.007	Single Plated
4	0.004"	0.0095-0.010"	0.008	Double Plated

2.3 Slicing Results

2.30 Run Summaries

Initial testing of the equipment and blades were done on 76 mm diameter, 1-0-0 orientation, single crystal silicon ingots. We could not do any initial testing on 100 mm material because the 16 inch blades could not accept that diameter during plunge slicing. With each type of blade, thickness and speed were set until we achieved acceptable yields.

SLICING RESULTS 76 mm CRYSTAL

RUN #	KERF (Mils)	SLICE THICKNESS (Mils)	SLICING SPEED (Inches/min)	AV. THICKNESS VARIATION (Mils)	AV. BOW (Microns)	NO. OF WAFERS	YIELD (%)
1	9.5	15.2	1.2	0.6	8	30	72
2	9.5	19.4	0.7	0.5	8	25	86
3	10.0	17.3	0.6	0.5	17	25	65
4	8.5	21.4	1.0	1.5	15	20	82
5	9.5	14.8	1.0	0.5	3	30	80
6	9.5	11.3	1.5	0.9	10	50	94
7	9.0	14.2	1.2	0.6	14	30	91
8	9.0	13.9	1.5	0.3	8	50	95
9	9.5	11.7	1.5	0.5	8	50	92
10	9.5	9.2	1.0	0.4	12	50	96

After we were satisfied with the performance of the blades and the equipment, we modified the saw to accept the programmable feed and rotation system. The 100 mm 1-0-0 orientation crystals were sectioned to about 4 inch lengths and were prepared for mounting on the rotating fixture. We had not had much experience with rotational slicing of silicon. The only rotational work had been on Gadolinium Gallium Garnet (GGG) and Sapphire. Both these crystals are very hard and are usually cut to about a 25 mil thickness at very slow feeds. It may take up to 20 minutes to slice one 3 inch diameter GGG wafer. After some initial work on mounting and feed and rotation tests, we began our slicing runs on various parameters. It became apparent fairly early in our tests that initial feeds had to be relatively slow and rotation had to be relatively slow. Once the blade had penetrated the width of the diamonds, feeds could be increased until we were close to the middle where the feed was reduced and rotation was sped up to minimize the central rib. A set of cams were fashioned to perform the above pre-programmed functions. Various slice thicknesses were selected and speed was set to yield acceptable results, i.e., good yield without visible cracks.

PROGRAMMED RUN SUMMARIES ON 100 mm 1-0-0 CRYSTALS

RUN #	KERF (Mils)	SLICE THICKNESS (Mils)	FEEDS (In./Min.) Min. Max.	ROTATION RPM Min. Max.	NO. OF WAFERS	YIELD %
11	9.0	14.8	0.30-1.0	15-30	50	92
12	9.0	15.5	0.20-0.8	3-25	50	95
13	10.0	15.2	0.30-1.0	10-20	50	89
14	9.5	12.2	0.10-0.50	5-30	50	72
15	10.5	11.9	0.10-0.50	5-30	50	83
16	9.5	12.1	0.10-0.50	5-30	50	85
17	9.5	9.8	0.07-0.30	7-20	50	51
18	9.0	10.2	0.07-0.50	7-20	50	55
19	9.5	10.0	0.07-0.45	7-20	50	43
20	9.0	8.5	0.05-0.30	10-20	30	40
21	10.0	8.2	0.05-0.25	10-20	30	42
22	10.0	8.0	0.05-0.30	10-20	30	38

2.31 Critical Factors

We did not have any problems in manufacturing blades to a thickness of 0.24 mm or less. The best results were with blades that were plated thin and had a minimum amount of grinding.

The 0.20 thick blades performed very poorly. There was very little clearance and we began to rub the core almost immediately after we began to slice.

Our best results were with blades 0.23-0.25 mm kerf loss.

With blades thinner than 0.24 mm we had to watch the traces on the non-contact sensor very carefully. During rotational slicing, we saw very little deviation in the blade during slicing. The traces would show problems near the end of the cut where the deviations occurred.

One of the biggest problems in rotational slicing is breakage of the wafers during initial entry and also about one-half of the way into the slice.

Mounting of the crystal becomes very critical in controlling edge chipping during rotational slicing. The surface of the crystal must be free of cracks and the physical axis of the boule must be perfectly aligned to the rotational axis of the rotating fixture.

We devised a set of V-Blocks to locate the boule and the mounting fixture. The crystal and mounting fixture would be rotated and located to the proper position with a dial indicator.

As shown in our slicing runs, the initial rotation and feed had to be slowed down to minimize edge chipping.

The most critical aspect of the set-up was the orientation of the axis of the rotating fixture with the axis of the blade. If deviations exceeded more than a few microns over 6 inches, the thinner wafers would begin to break during slicing. We found that the alignment had to be readjusted periodically as the fixture and crystal were indexed. The thin wafers had to be recovered automically using a vacuum chuck. The timing of the vacuum became very critical.

2.32 Optimization

The best feeds and speeds are represented by the cam shapes shown in figure 2. As we began to decrease slice thickness, we also had to dramatically reduce cutting speeds as shown in our slicing summaries. At the lower thicknesses, initial feed became very critical and the machine had to be slowed considerably.

3.0 CONCLUSIONS

Although Rotational Slicing allows much lower kerf

losses than conventional plunge slicing, the drawbacks of this technique make it less productive than conventional plunge cutting.

Equipment costs for the rotational mechanism are higher than a conventional saw.

Skilled operators are needed to watch the saw and to make adjustments if there are problems. An operator could run more saws in conventional plunge cutting.

Cutting speeds are slower with rotational slicing.

Yields are poorer at a given thickness with rotational slicing.

Although kerf losses are higher with larger 22 inch blades, their performance with plunge cutting would yield lower cost 100 mm wafers.

4.0 RECOMMENDATIONS

Present analysis indicated that crystal cost can be reduced by increasing the size of Czochralski and other types of ingots. By using conventional I.D. wafering, and reducing the requirements for wafers per inch, present state of the art can be improved. At 18 wafers per centimeter, 6 inch Czochralski ingots can be sliced at a combined kerf plus thickness of 0.022 inches which is within the capabilities of I.D. technology. The extra kerf loss involved in plunge cutting can far outweigh the problems encountered in rotational slicing.

Kerf loss can also be reduced. Present core thickness on a 22 inch blade is 0.006 inches. There are some experimental blades being made below 0.005 inches core material.

We recommend work toward finding new materials for use in blades. Our investigation has shown that at the present time 300 series stainless steel is the best material for I.D. blades; however, there are other materials such as H-11 tool steel and copper berylium alloys that may be stronger and allow thinner blades. We were not able to find other exotic materials in sheet form suitable for making blades.

5.0 NEW TECHNOLOGY

No new technology was developed during this contract.

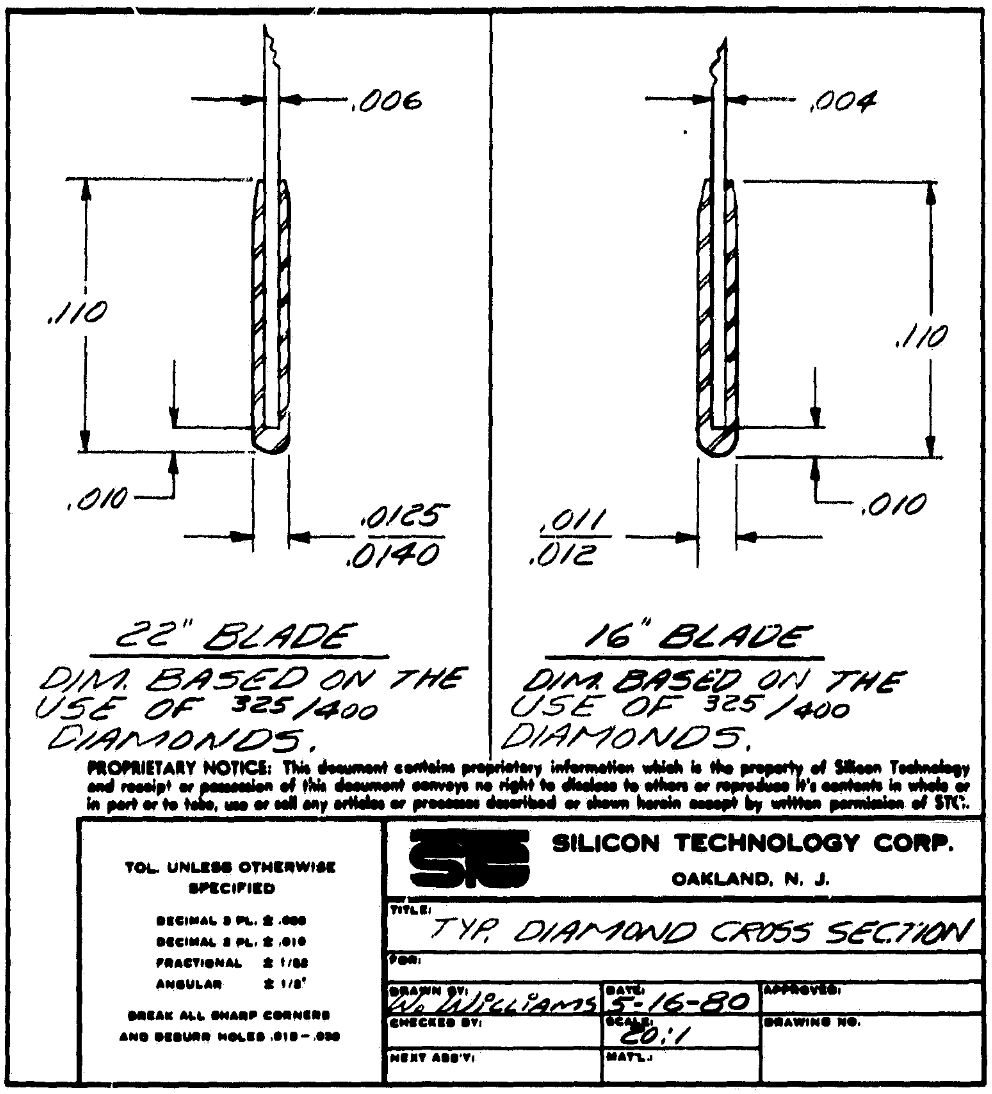
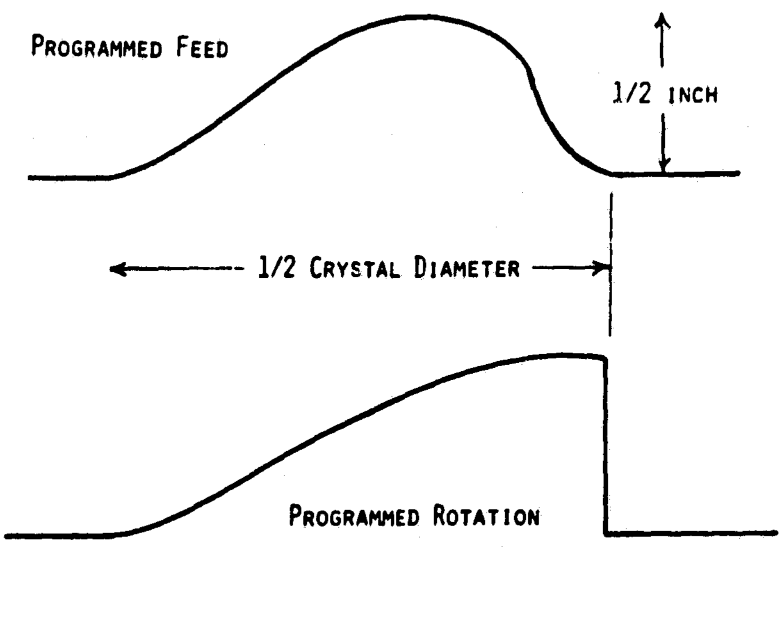
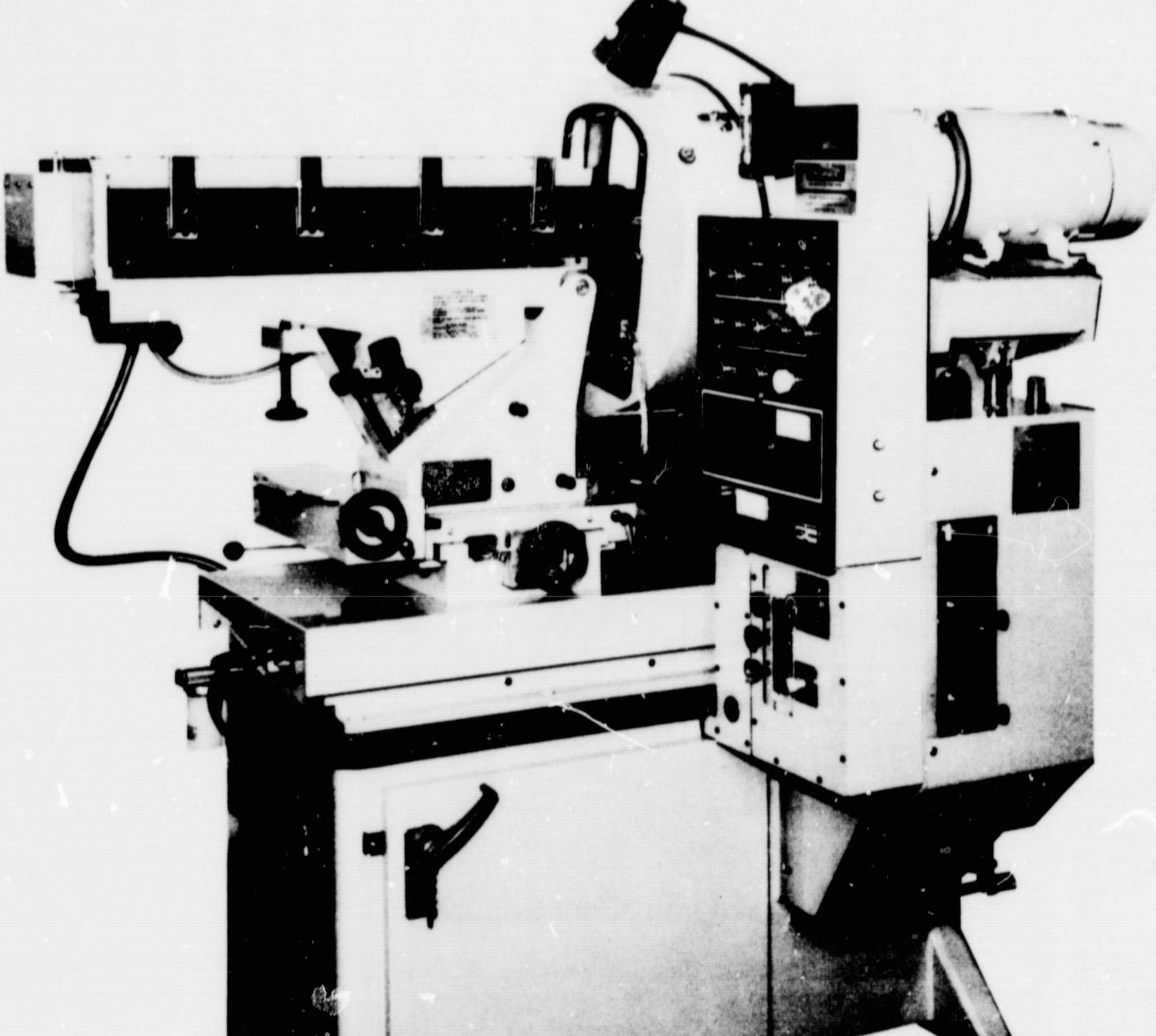


FIGURE 1

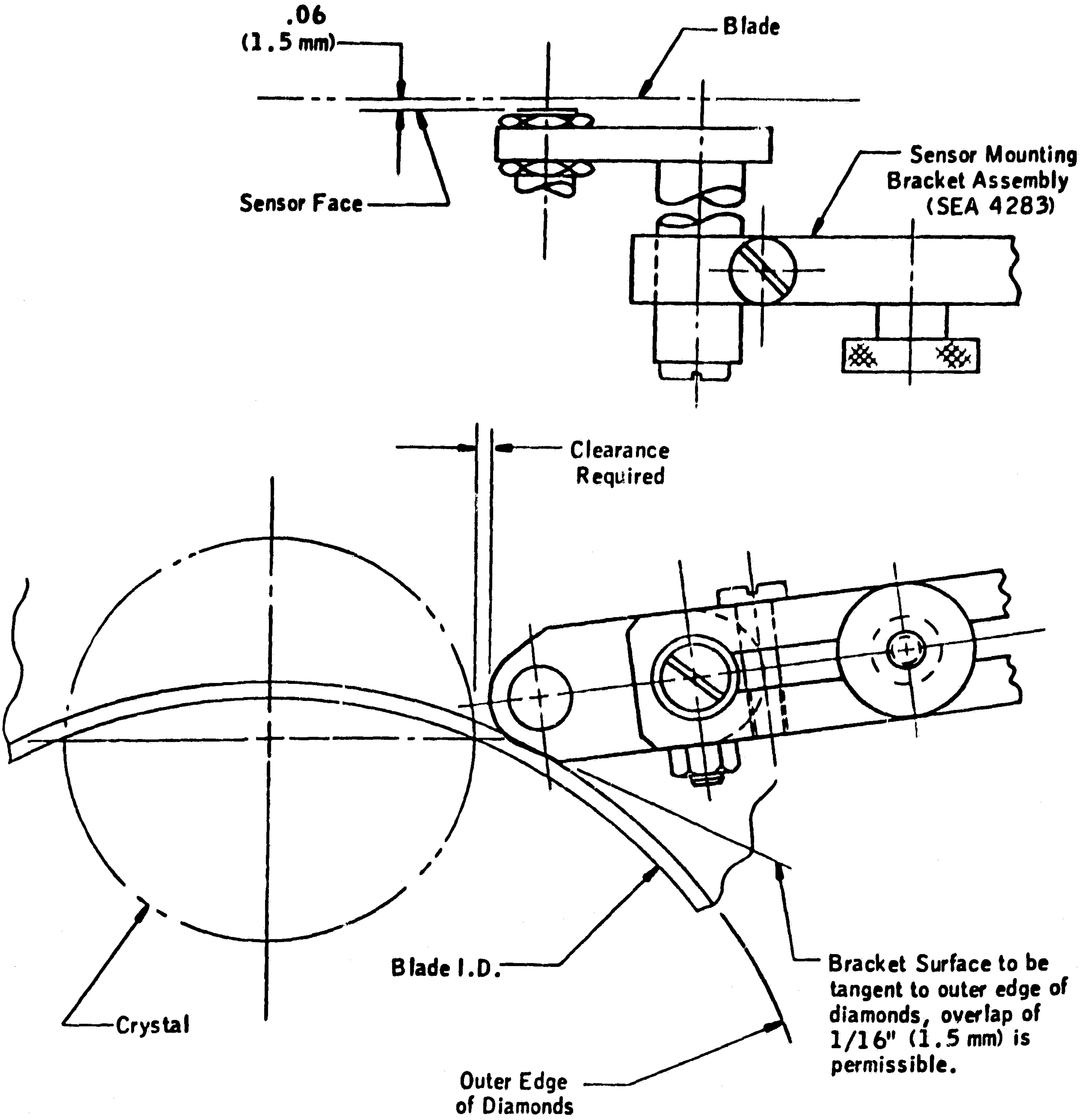
Program Cam Shapes





STC I.D. SLICING MACHINE

FIGURE 3

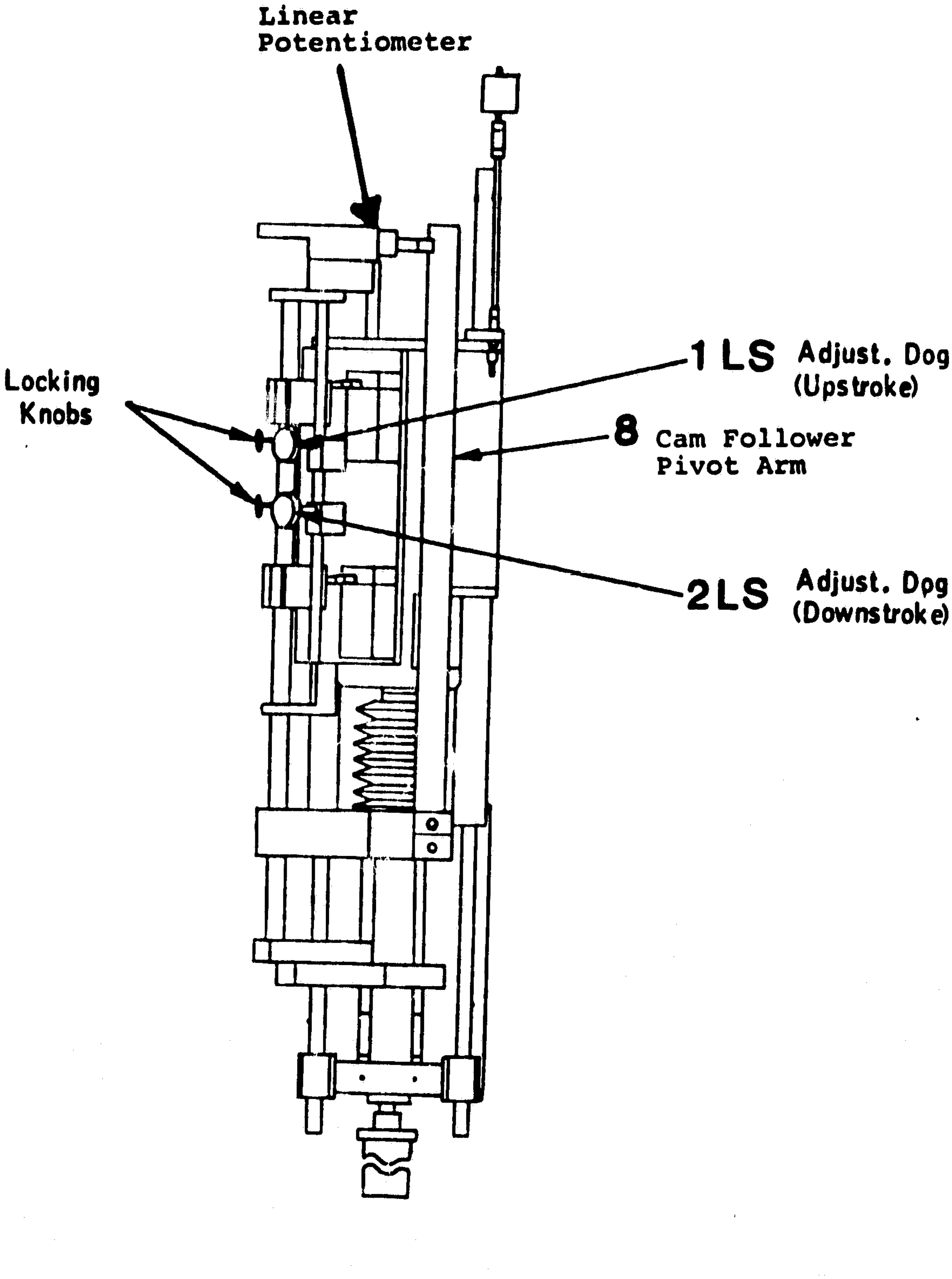


DYNATRACK SENSOR ALIGNMENT

FIGURE 4

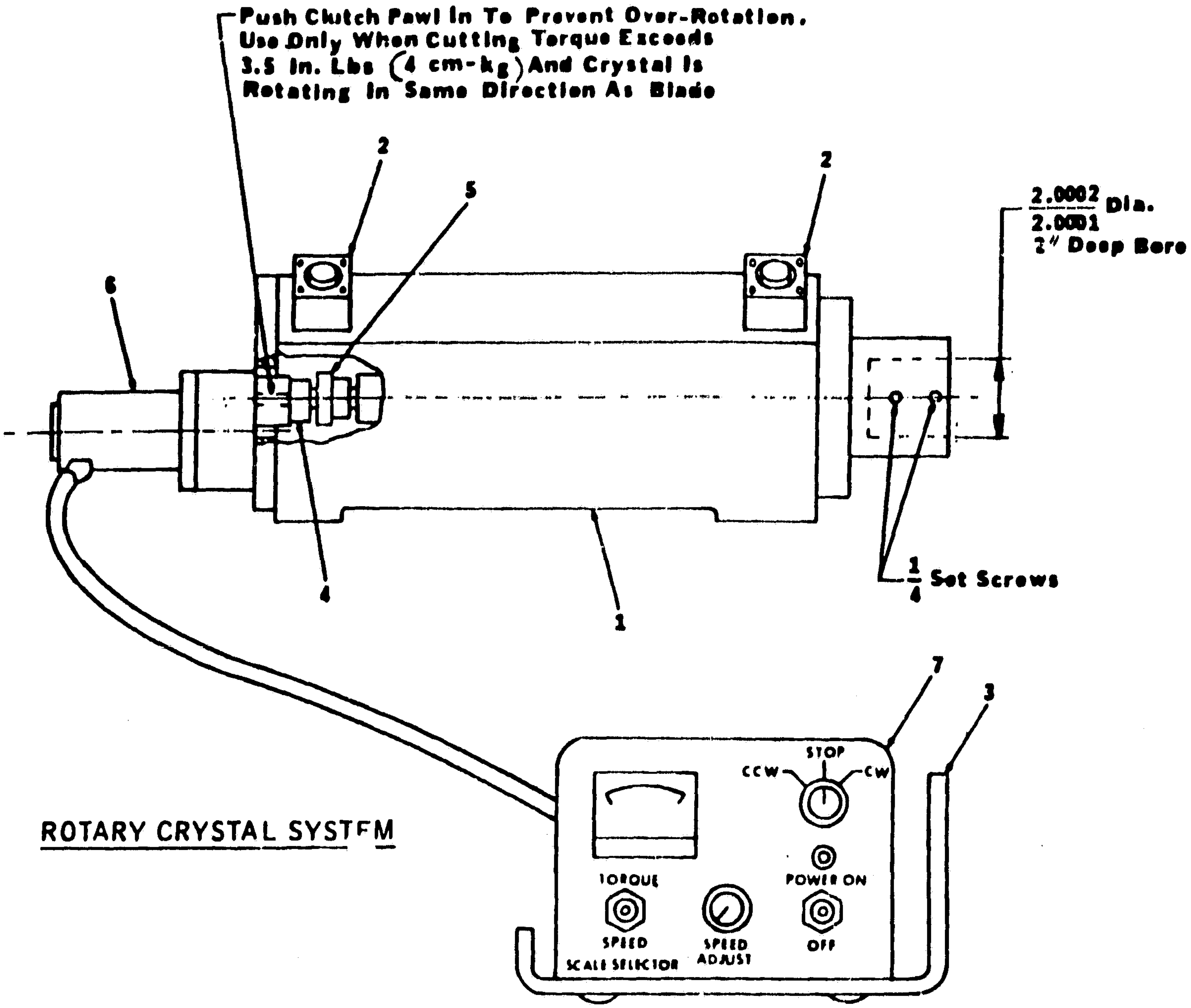
PROGRAMMABLE FEED SYSTEM

ELECTRIC PART NO. SEA 4302



FRONT VIEW

FIGURE 5



ROTARY CRYSTAL SYSTEM

Item	Description
1	Rotary Crystal Assembly
2	Plunger Assembly
3	Controller Mounting Bracket
4	Slip Clutch
5	Coupling Assembly
6	Motor
7	Motomatic Control

FIGURE 6